Dynamics, Structure, and Emission of Electron-Positron Jets

Amir Levinson

School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel

Abstract: The theory of gamma-ray emission from $e^\pm$ jets and the implications for jet formation, dynamics and structure are reviewed. In particular, possible carriers of the jet's thrust on small scales, the transition from electromagnetic to particle dominance in Poynting flux jets, formation of pair cascades, synchrotron emission by cascading pairs, and formation of shocks due to unsteadiness in the jet parameters are considered, with emphasis on the observational consequences. Some recent progress in modeling transient emission from blazars is also briefly discussed.

1 Introduction

There is little doubt that the gamma-ray emission seen from EGRET blazars is highly anisotropic (see ,e.g., review by Schlickeiser 1996). In most models of high-energy emission from AGNs the energetic gamma-rays observed are attributed to emission processes in a relativistic jet pointing in our direction. This view is strongly supported by the exclusive association of the EGRET AGN sources with compact radio sources (von Montigny et al. 1995). However, the physics of jet formation and dynamics is not well understood. Moreover, there are several unresolved issues related to the emission from jets. Further progress in our understanding of these systems requires i) additional observations, particularly multi-waveband campaigns and coverage of the 10-100 GeV band, and ii) theoretical tools which would enable interpretation of such data. It is, therefore, important to study quantitatively various models of gamma-ray blazars.

This talk focuses on the physics of electron-positron jets. Formation of $e^\pm$ jets, conceivable carriers of energy and momentum, and observational

constraints on jet dynamics and structure near the central engine are considered first. Emission from leptonic jets is considered next. Finally, preliminary work concerning a specific mechanism for production of flares in blazars is discussed.

2 Observational characteristics of gamma-ray blazars

The gamma-ray luminosities observed in blazars span a wide range, with the most powerful sources exhibiting isotropic luminosities during high states as high as 10^{49} ergs s^{-1}. The spectra in the EGRET band can be well fitted by power laws, with energy spectral indices in the range 0.7-1.5. At least in two cases (Mrk 421 and Mrk 501) the spectrum extends into the TeV regime. Some FSRQ exhibit spectral breaks (peaks) at a few MeV with a slope change $\Delta\alpha > 1$ in some cases. A second, low energy (radio to soft X-ray) spectral component peaking in the submm to IR regime is also characteristic to many blazars (e.g., Brown et al. 1989). This low energy component is commonly ascribed to synchrotron cooling of relativistic electrons accelerated locally in the jet (Blandford & Königl 1979). The high energy component that peaks at MeV energies is probably produced by inverse Compton emission of these electrons. However, the source of scattered photons is still unresolved, as discussed below.

Regarding the temporal behavior of blazars, doubling times as short as a few hours have been reported for some EGRET flares (e.g., Mattox et al. 1997), and an even shorter variability time scale has been inferred for Mrk 421 at TeV energies (Buckley et al. 1996), implying very compact emission regions. Recent observations reveal time lags of a few weeks to months between gamma-ray and radio outbursts (Reich et al. 1993; Zhang et al. 1994). In some sources there are also indications for correlations between the optical and gamma-ray emission (e.g., Maraschi et al. 1994; Wagner, 1996). Such data can be used to impose constraints on the relative location of the emission regions at different energies, and perhaps on the emission mechanism.

3 Electron-Positron jets

3.1 The small scale structure

The pair content of leptonic jets is limited at small radii by annihilation. For a conical jet with an opening angle $\sim \Gamma^{-1}$, where Γ is the bulk Lorentz factor, the maximum jet's thrust that can be carried by sub-to- mildly relativistic pairs is given by (Blandford and Levinson 1995)

$$L_e = \left(\frac{\sigma_T}{2\pi\sigma_{ann}}\right)\left(\frac{m_e}{m_p}\right)\left(\frac{r}{r_g}\right)\Gamma L_{Edd} \simeq 5 \times 10^{45}\Gamma_1 r_{16} \quad \text{ergs s}^{-1}, \quad (1)$$

where r_g is the gravitational radius, $\Gamma_1 = \Gamma/10$, and r_{16} is the radial distance from the putative black hole in units of 10^{16} cm. The enormous gamma-ray luminosities observed from the powerful sources imply jet power of at least 10^{46} - 10^{47} ergs s^{-1}. Consequently, if jet formation is completed close to the black hole (at a distance of a few gravitational radii say) then the carrier of energy and momentum at radii below $r_{ann} \sim 10^{-2}$ pc must be either baryons, Poynting flux, or ultra-relativistic pairs for which the annihilation cross section is sufficiently reduced by KN effects. Alternatively, the jet may be accelerated and collimated over a range of radii encompassing r_{ann}. Hadronic jet models (Mannheim 1993; Dar & Laor 1997) will not be considered here (see e.g., Celotti 1997; Mannheim 1997). The possibility that the jet power is transferred outwards by ultra-relativistic pairs requires most of the jet power to be dissipated below r_{ann} in ERC models (which invoke the presence of external, dense radiation field) if the jet accelerates to Γ in access of that of the frame in which the radiation field is roughly isotropic. Such a model can account for the MeV peak seen in several sources (since gamma-rays having energies below a few MeV can escape without being absorbed by pair production on the background photons, as discussed in §3.2 below). However, the gamma-ray spectrum above the peak is anticipated, in this scenario, to be much steeper than those typically observed. Furthermore, this may be problematic for unified models in which the radio luminosities of extended radio sources are associated with the jet power on large scales. The reason is that the observed luminosity of extended lobes is predicted to be much smaller than the anisotropic gamma-ray luminosities (i.e., after correcting for beaming effects) inferred in blazars, in conflict with observations.

In the case of a cold e$^{\pm}$ beam the production rate of soft X-rays by the interaction of the cold electrons with the ambient radiation field is related to the electron kinetic power, $L_e(r)$, through (Levinson 1996b),

$$\frac{dL_X}{d\ln r} = L_e(r)\frac{r}{l_c}, \tag{2}$$

where

$$l_c/r \simeq 0.5(\chi L_{x46})^{-1} r_{16} \Gamma^{-1} \tag{3}$$

is the ratio of inverse Compton cooling length of streaming electrons to jet radius. Here $10^{46} L_{x46}$ ergs s^{-1} is the luminosity of the background radiation, and χ the fraction of this luminosity that is intercepted by the jet. For a reasonable choice of parameters we find that this ratio becomes smaller than unity below r_{ann}. Clearly, in order to avoid catastrophic radiative drag and hence X-ray overproduction (i.e., $L_X < L_j$) the fraction of energy flux carried by electrons (positrons) in the inner jet, which for an outflow consisting of purely e$^{\pm}$ plasma equals Γ_A^{-1}, Γ_A being the Lorentz factor associated with the Alfvén speed of the outflow with respect to its rest frame, must be smaller than the ratio of radiative cooling time to outflow

time l_c/r. The constraint on L_e might be even more stringent in sources in which the soft X-ray luminosity is inferred to be much smaller than the jet power (e.g., Sikora et al. 1997). The above conclusions may be substantially changed if the jet consists of a relativistic core shielded by a slower, hot, Thomson thick outflow.

A scenario in which energy extracted from a spinning black hole is transfered outwards in the form of a Poynting flux jet which is collimated by a surrounding hydromagnetic wind emanating from an accretion disk, has been discussed recently (Blandford & Levinson 1995). In this model the jet undergoes a transition from electromagnetic to particle dominance in the vicinity of the annihilation radius r_{ann} (Levinson & Blandford 1995). The conversion of electromagnetic energy into pairs and X/gamma-rays can result from (Levinson 1996b) either the interaction of the cold $e^{\pm}$ beam with the ambient radiation, or strong dissipation in the gamma-ray emitting region (beyond r_{ann}), e.g., due to the formation of dissipative fronts by unsteady jet injection (Romanova & Lovelace 1997; Levinson & van Putten 1997). In the former case, copious pair production ensues once the jet is accelerated to bulk Lorentz factor in excess of $E_{thr}/m_e c^2$, the threshold energy above which the opacity to pair production on background photons exceeds unity. For the standard spectrum (Blandford and Levinson 1995) $E_{thr} \sim (m_e c^2)^2/E_{max}$, where $E_{max} \sim 100$ KeV is the maximum cutoff energy of the scattered spectrum. The asymptotic Lorentz factor is then limited to $\Gamma \sim m_e c^2/E_{max} \sim 10$ (Levinson 1996b), compatible with that inferred from superluminal expansions (Vermeulen & Cohen 1994). One problem with this mechanism is that it requires the spectrum of the soft photons intercepted by the inner jet (but not by the gamma-ray emitting jet) to be sufficiently flat in order to avoid X-ray overproduction (Levinson 1996b). In the latter case it is envisioned that continues fluctuations of the outflow steepen into a train of shocks above the cooling radius. The shocks thereby created propagate along the jet and dissipate a substantial fraction of the jet energy over the extended, gamma-ray emitting region. The resultant spectrum then peaks in the MeV band, as explained below. Frequent formation of such shocks can lead to a slowly varying (quiescent) emission, whereas occasional creation of a very intense front may lead to a gamma-ray flare, as discussed further in §3.4.

3.2 Synchrotron and inverse Compton emission

As already mentioned above, the radio to UV/soft X-ray continuum spectrum is successfully interpreted as synchrotron radiation by relativistic electrons (positrons) accelerated in situ, while the high-energy spectral component is presumably due to inverse Compton emission of these electrons. The source of seed photons can be either the synchrotron radiation itself (SSC mechanism, e.g., Königle 1981; Ghisellini & Maraschi 1989; Bloom &

Marscher 1993), nuclear radiation that directly enters or, alternatively, scattered (reprocessed) across the jet by surrounding gas (Dermer & Schlickeiser 1993; Blandford & Levinson 1995; Sikora, Begelman, & Rees 1994; Marcowith, Henri, & Pelletier 1995), or jet synchrotron emission reprocessed by the broad line clouds (Ghisellini & Madau 1996). The ERC mechanism is likely to dominate in the powerful gamma-ray quasars if they posses isotropic UV/X-ray luminosities as high as those typically observed in radio-quiet sources (e.g., Sikora, et al. 1997). Moreover, SSC models have difficulties explaining the high ratio of luminosities of the high-and low-energy spectral components often seen in the powerful blazars (Mannheim 1997; Sambruna et al., 1997; Sikora, et al. 1997). This mechanism is more likely to be important in the weak BL Lac objects in which the luminosity of the underline nuclear radiation appears to be low.

The UV/soft X-ray background may also contribute a large opacity to pair production at small radii (Dermer & Schlickeiser 1993; Sikora et al. 1994; Blandford & Levinson 1995). To be concrete, for a soft photon intensity typical to radio quiet quasars, the gamma-spheric radius below which the pair production opacity becomes larger than unity increases with gamma-ray energy and lies in the range 10^{-3} to about 0.1 pc at EGRET energies (Blandford & Levinson 1995). This imposes a constraint on the location of the gamma-ray emission region.

In one-zone models (e.g., Sikora et al. 1994), the broad-band emission (with the possible exception of the radio emission) is assumed to originate from a small region where dissipation of the bulk energy predominantly takes place. (In the ERC version this region should be located far enough from the central source to avoid attenuation of the highest energy gamma-rays observed.) Correlations between the fluxes at different energies over a broad energy range may then be naively anticipated, although situations wherein variations in the energy distribution of emitting electrons may lead to a different behavior can be envisioned. Such a prediction appears to be consistent with the claimed correlations between optical and gamma-ray emission (Wagner 1996). Unfortunately, this observation is not discriminatory since such correlations are predicted also by inhomogeneous pair cascade models, given the EGRET sensitivity (Levinson 1996a). The reported delays between gamma-ray and radio flares (Reich et al. 1993) are not in conflict with the one-zone model provided that the emission region is located well within the radio core. If the emission region is at a distance of 10^{17} - 10^{18} cm from the central source, as suggested by Sikora et al. (1994), then the gamma-ray spectrum should exhibit a high-energy cutoff in the range 10-100 GeV. This energy band is presently uncovered by any instrument. It is hoped that the next generation gamma-ray telescope (like GLAST) will help elucidating the spectrum of gamma-ray blazars in this range.

In the inhomogeneous pair cascade models (Blandford & Levinson 1995; Marcowith, et al. 1995), which assume continues dissipation and electron

acceleration along the jet, the observed gamma-rays at a given energy are created near the corresponding gamma-spheric radius through pair cascades. As a result, the emitted gamma-ray spectrum is produced over a large range of jet radii, with higher energy gamma-rays coming from larger radii, and reflects essentially the intensity of the ambient radiation as well as the variation of electron injection rate with jet radius. The energy distribution of the radiating electrons is determined by the cascade process and is highly insensitive to the injected electron spectrum, provided that electron acceleration is efficient. In contrast to the one-zone models, inhomogeneous pair cascade models predict spectral evolution during gamma-ray flares, with slower (or later) variations of the gamma-ray flux at higher energies. The detection of such a spectral evolution in quasars requires coverage of energy range broader than that covered by EGRET with a better sensitivity, and should be one of the objectives of future missions. The simultaneous X-ray/TeV flare and the lack of significant changes in the EGRET flux seen in Mrk 421 (Macomb et al. 1995; Takahashi et al. 1996) is problematic for this model. The absorption by pair production on the background photons gives rise to a steepening of the gamma-ray spectrum at energies above about $(m_e c^2)^2/E_{max} \sim 10$ MeV (E_{max} is the high energy cutoff of the ambient radiation mentioned above) and, therefore, can account quite naturally for the MeV bump.

The cascading pairs are also responsible for the synchrotron spectrum. A detailed analysis of synchrotron emission from inhomogeneous pair cascade jets (Levinson 1996a) shows that the radio to UV spectra observed typically in blazars can be reproduced by the model quite naturally, provided that the product of pair injection rate and magnetic field declines sufficiently steeply with radius (steeper than r^{-3}). The turnover from flat to a steeper power law spectrum results, in the model, from the strong suppression of the synchrotron emissivity below r_{ann}, owing to rapid pair annihilation (see §3.1). A second break at higher frequencies (observed in some sources) can be reproduced by controlling the maximum electron injection energy. Further, for typical parameters the radio (GHz) photospheres are located well beyond the EGRET gamma-spheres whereas the submm to optical emission region coincides with the jet section where EGRET gamma-rays are produced. Given the sensitivity of EGRET, the latter is consistent with the optical/gamma-ray correlations discussed above.

3.3 Local electron acceleration and maximum injection energy

The maximum energy attainable by an electron depends on the acceleration rate. Shock acceleration can give rise to a maximum acceleration rate on the order of the gyro-frequency of accelerated particle (Blandford and Eichler 1987; Kirk 1997). For electrons (positrons) this yields a maximum Lorentz factor, as measured in the comoving frame,

$$\gamma_{max} \simeq 10^8 (\eta/B)^{1/2}(1+\mathcal{E})^{-1/2}, \tag{4}$$

where η is the acceleration rate in units of the electron gyro-frequency, and

$$\mathcal{E} = \frac{U_x}{U_B} \simeq 6 \times 10^5 \frac{\chi L_{x46} \Gamma_1^2}{r_{16}^2 B^2} \tag{5}$$

is the ratio of comoving energy densities of scattered radiation and magnetic field. Note that this ratio is independent of radius if $B \propto r^{-1}$. For a reasonable choice of parameters (cf. Levinson 1996a) we find that the maximum electron energy is not likely to exceed a few TeV or so in the powerful sources. Higher energies may be attainable in faint BL Lac objects provided that the magnetic field is sufficiently weak. The fact that Mrk 421 and Mrk 501 have been detected at TeV energies implies that at least in these sources electron injection must be very effective. It is not known whether the high energy spectrum of FSRQ extends into the TeV regime. TeV detections of FSRQ would impose severe constraints on ERC models. Observations of FSRQ in the energy range 10 GeV to a few hundred GeV, where absorption by the intergalactic IR background is strongly suppressed, can provide valuable information regarding the in situ acceleration mechanism and the location of the gamma-ray emission region.

3.4 Time dependent models

Various episodes may lead to time variability of blazar emission. For example, sudden changes in particle injection rate and/or magnetic field, changes in the bulk speed, or temporal changes of the intensity of ambient radiation in ERC models. Presumably, different mechanisms would give rise to different characteristics of the time dependent emission in blazars. It is, therefore, desirable to explore different variability models, and compare model predictions with observations. Below, we briefly discuss a specific model of transient jets.

Romanova & Lovelace (1997) proposed a model of gamma-ray and VLA flares in which fluid collision in a pointing flux jet leads to the formation of radiating fronts propagating down the jet. Under the assumption of rapid magnetic field dissipation (and therefore slow expansion of the front) they derived a set of differential equations governing the acceleration, heating and cooling of the front. The solution of the system yields the predicted light curves. In their treatment they ignored gamma-ray absorption on external, hard X-ray photons, which is expected to be important at small radii as explained above, and, therefore, obtained almost simultaneous flaring at frequencies above the synchrotron self-absorption frequency. Further, the energy distribution of shocked particles is assumed a priori in their model.

The formation, evolution and structure of such fronts have been carefully examined recently by Levinson & van Putten (1997), using analytic

and numerical approach. By treating the magnetic field in the front as a free parameter they determined the dependence of the front parameters on the rate of magnetic field dissipation. The distance from the injection point at which disturbances steepen into shocks is found to be roughly $c\Delta t \Gamma^2 \Gamma_A^2/3$, where Δt is the characteristic time change of the outflow parameters (of order the dynamical time in the injection zone). This model can be extended (Levinson, in preparation), within the framework of the inhomogeneous pair cascade model, to incorporate radiative cooling and pair cascades self-consistently, by coupling the front equations with the equations governing the evolution of the pairs, gamma-rays and synchrotron intensities in the front. This would enable self-consistent calculations of light curves as well as spectral evolution during flares over a range encompassing radio to gamma-ray energies under different conditions (e.g., magnetic field dissipation rate).

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